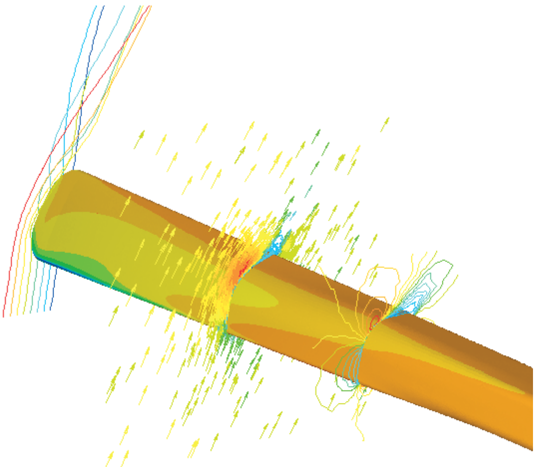
Propelling the 1903

By Christoph Hiemcke, Fluent Inc.

Propeller of the AIAA-LA replica



Pressure contours at the surface, tip pathlines, and velocity information in the form of line contours and vectors illustrate the flow around the propeller for an advance ratio of J=0.69

One of the great achievements of the Wright Brothers was their design of the two counter-rotating propellers used on the 1903 Wright Flyer. During the past year, FLUENT has been used to simulate the propeller under a number of different flight conditions, and the results have contributed to the design of one of the Flyer replicas being built. Before describing the aerodynamics of the propellers in modern terms, it is interesting to turn the clock back one hundred years, to the time when the Wright Brothers were busy with the design.

Following successful glider tests at Kitty Hawk in the summer of 1902, the Wright Brothers returned home to Dayton and focused on the design of the propulsion system. Orville preoccupied himself mostly with the motor, while Wilbur concentrated on the propeller. Realizing that the design of marine propellers at the time was based primarily on empirical methods, they set out to develop a theory for airplane propellers. They combined the momentum theory of W.J.M. Rankine and R.E. Froude and the blade element theories developed by Wm. Froude and S. Drzewiecki. A derivative of their propeller theory is still used routinely today. The approach is as follows: the blade is split into a number of spanwise slices or elements, and then contributions to the thrust and torque from each segment are computed using the local flow velocity and angle of attack. Corrections are made for the losses associated with the leakage of air around the tip, and all contributions are summed to arrive at the total thrust and torque for the blade. The Wright Brothers used a single blade element and chose to analyze the flow at the 5/6 (83.3%) spanwise position, a location they referred to as the blade's "center of pressure." They had measured the aerodynamic performance of a number of airfoils, and they settled on Wright Airfoil Number 9 for their propeller analysis.

The brothers intuitively recognized that the performance of a propeller during a static test would be quite different from the performance during forward flight, so they tested a small (28" diameter) fan in their wind tunnel at 1,600 rpm and at a forward speed of about 25 mph. Their first full-scale propeller underwent static testing in February 1903, whereas the final 1903 propellers were first tested in November of that year, just weeks before the first flight. Each propeller had been manufactured by gluing together three planks of kiln-dried spruce, and then carving the resulting beam. The Wright Brothers measured a static thrust of 67 pounds per propeller, at 350 rpm. Wilbur predicted an efficiency of 66 % (efficiency is the ratio of the power available to propel the airplane to that required to spin the propeller). Luckily, the propellers performed better than that, since their airplane came in overweight by 75 pounds. Without the additional efficiency of the propeller, the craft would not have flown!

The Wright Brothers conducted four flights on December 17th, 1903, but the Flyer was severely damaged by a wind gust later in the day. The propellers survived intact and were reused for the testing of the 1904 Flyer; they were eventually broken in a flight demonstration in May 1904. After that, they were placed into the crate that contained the broken parts of the 1903 Flyer. They now belong to the National Park Service.

One of the replicas being readied for the centennial flight this year was designed and built by the Los Angeles section of the American Institute of Aeronautics and Astronautics (AIAA-LA). This replica incorporates several deviations from the historic design that were introduced to improve the safety of the airplane. One such design change is that the more modern engine will spin authentic replicas of the 1903 propellers at speeds above the historic 350 rpm. This will help to prevent stalls by increasing the airspeed.

In the first 3D Navier-Stokes analysis of the Wright propellers, FLUENT was used to shed light on the aerodynamics of the propeller, especially at higher speeds. The solid model of the propeller was made in GAMBIT, based on the blueprints made by Louis B. Christman while the Flyer and its propellers were at the Science Museum in London between 1928 and 1948. Christman's blueprints provide the shape of the propeller profile at five spanwise sections, and these profiles were drawn in GAMBIT. The overall radius of the propeller is 51 inches (4' 3"). The GAMBIT model differs from the original only near the hub, since the blueprint provides no mathematical definition of the transition from an airfoil profile to the rounded, rectangular root. However, this deviation should not affect the aerodynamics much. Only one propeller blade was modeled in a 180-degree rotationally periodic domain. The root of the propeller blade was

Wright Flyer

placed at the center of a hemispherical domain whose radius was about 20 times the blade span. A triangular surface mesh was generated, and TGrid was used to generate five layers of wedges in the boundary layer, and tetrahedral elements elsewhere for a total of 1.79 million cells.

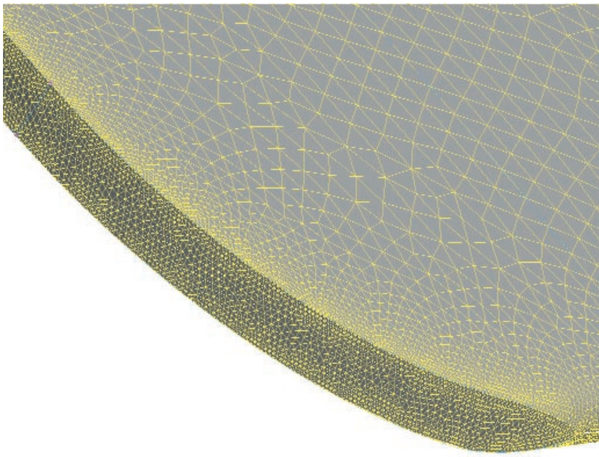
It was assumed that the problem was steady when viewed by an observer spinning with the blade, so the single (rotating) reference frame (SRF) model was used. For the Wright Flyer, this assumption meant that the effects of the ground, wings, and propeller drive components were neglected, along with all aeroelastic deformations of the blades. Because of the anticipated widespread separation, the realizable k-ε turbulence model with enhanced wall treatment was chosen. The flow was assumed to be turbulent everywhere. To help the solution converge, the rotational speed was increased in increments. Once the flow was converged at the final rotational speed, a second order solution was performed.

To validate the model, it was first applied to the static condition at 350 rpm, for which the Wright Brothers had recorded a thrust of 67 pounds per propeller. The FLUENT result was 69.5 pounds, which represents a five percent difference, and is quite acceptable given the numerous assumptions made. The static case is characterized by significant amounts of flow separation, so is perhaps the most difficult case to solve. Once it was completed, however, the FLUENT model was run over a range of operating conditions to produce propeller performance charts. At cruise conditions, the results showed that the flow was remarkably well attached.

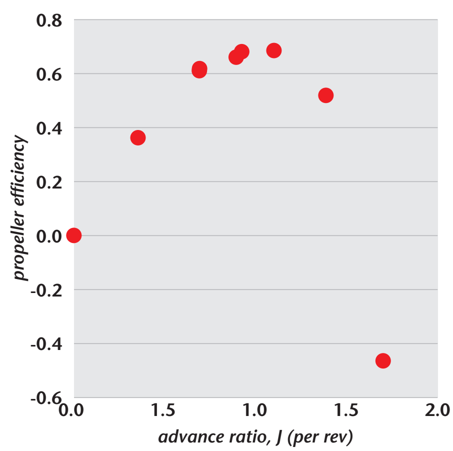
Important insight can be gained from a plot of propeller efficiency vs. advance ratio (J), which is the ratio of the freestream speed to the rotational speed at the tip. Simulations were run for advance ratios that span the actual flight. With a propeller speed of 350 rpm and the Flyer at a standstill on the launch rail, J has a value of 0. Halfway through the takeoff run, J = 0.35, and at the end of the takeoff run, J = 0.69. Three cruise conditions were modeled, corresponding to J = 0.89, 0.92, and 1.1. After throttling back at full forward speed, the advance ratio increases to J = 1.4. Finally, two cases were considered with the aircraft descending and the engine idling: J = 1.7 and 2.1.

The results of these simulations indicate a peak efficiency of just over 70%, which is one of the impressive achievements of the Wright Brothers. This is particularly true if one considers that the highest efficiencies of modern propellers are about 85%. The present result compares well to Wilbur's prediction of 66%, especially if one considers that the Wright Brothers had underpredicted the efficiency.

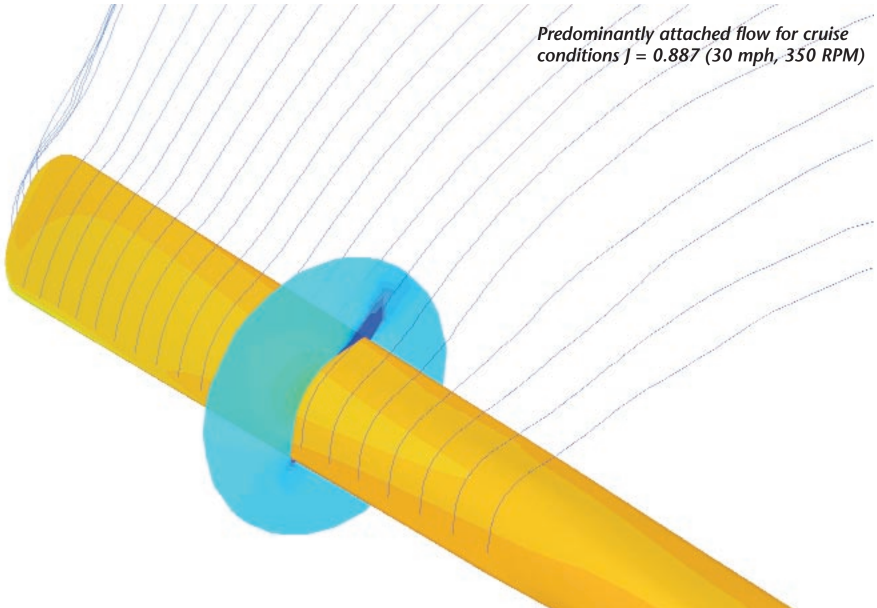
The Wright Brothers would surely have enjoyed seeing the flow visualized by means of CFD. It would have allowed them to witness and grasp the separation phenomenon for the first time, and they would have had proof that their design was outstanding for cruise conditions. ■



Surface mesh near the propeller tip



Efficiency curve, based on the CFD results



Predominantly attached flow for cruise conditions J = 0.887 (30 mph, 350 RPM)

more.info@
www.wrightflyer.org
AIAA Los Angeles Chapter, Wright Flyer Project